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Structural, economic and material comparison of various steel grades under fatigue loading

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CHAPTER ONE: STEEL

1.1 STEEL PRODUCTION

The raw material for steel are iron ore (in South Africa, they are mined at Mapochs in the Eastern Transvaal, for Highveld steel), coal (mined at Witbank South Africa also for Highveld), and dolomite. These products are fed to a furnace that converts them into molten steel.

The molten steel is then cast in ingots or, by means of a modern continuous casting process, cast directly into slabs or blooms that are subsequently reheated and rolled into plates or sections. At the Highveld steel plant, they have 5 continuous casting machines: 1 brittle machine, 3 bloom machines and a slab caster. The mould size on the billet machine can range from 98 mm^2 up to 140 mm^2 and can be changed conveniently thus the diverse needs of a wide range of billet re-rolls can be met.

For example, Highveld has five continuous casting machines: 1 billet machine, 3 bloom machines and 1 slab caster. The details of these machines are shown in table 2.1 below.

Table 2.1 – Cast standard sizes

Continuous casting standard size configuration		
Caster one (bloom)	229 x 184 mm	4 strand
Caster two (bloom)	305 x 254 mm	2 strand
Caster three (bloom)	559 x 305 mm	2 strand
Caster four (billets)	98mm, 120mm, 130mm, 140mm squares	4 strand
Caster five (slabs)	180mm x 1450 – 2000mm and 250mm x 1000 – 2050mm	single strand

Courtesy of Highveld Steel and Vanadium Corporation Ltd.

The final mechanical properties of the steel are strongly influenced by the chemical composition and melting practice, as well as by rolling practice, including the finishing temperature and cooling rate. The steel is also subjected to subsequent heat which also has an effect on the properties.

These bloom sizes are rolled into finished products in the structural mill. This is a semi-automated combination mill for rolling universal columns, parallel flanged beams, stand joists, channels, angles, flats, rounds and squares. The blooms are first rough shaped in a breakdown stand, passed through and further shaped in a 32” 2-Hi-roughing stand, then transferred to the combination finishing stand for final rolling. After the Universal beams, columns, rolled steel joints and universal flats have been rough shaped they are sawn to length using hot-saws and allowed to cool before straightening.

*Marking and Bundlin*g: For highveld steel, brand mark and section size can be rolled at intervals into the surface of each structural shape and size, mass per metre and cast number are stenciled or hand stamped onto the surface near the end.

For domestic deliveries, rolled and cast steel products are generally not bundled. However, for export abroad, the steel is bundled preferably 4/5 tons or to the customers requirement.

Below is a table and description for Standard supply parameters for rolled billets:

Table 2.2 – Standard supply parameters for rolled billets
Quantity: +/- 5% minimum

Tolerances for rolled billets					
Nominal size (mm)	Across Face Tolerance (mm)	Nominal Diagonal (mm)	Maximum diagonal (mm)	Minimum Diagonal (mm)	Corner Radius (mm)
92,0	+/-1.2	121.8	123.0	120.6	10.0
98,0	+/-1.2	128.1	129.3	126.9	12.7
100,0	+/-1.2	130.9	132.1	129.7	12.7
102,0	+/-1.2	133.7	134.9	132.5	12.7
105,0	+/-1.6	138.0	139.6	136.4	12.7
112,5	+/-1.6	145.8	147.4	144.2	16.0
127,5	+/-1.6	163.9	165.5	162.3	19.0
130,0	+/-1.6	168.1	169.7	166.5	19.0
140,0	+/-1.6	183.5	185.1	181.9	17.5
150,0	+/-1.6	195.6	197.2	194.0	20.0
170,0	+/-2.4	223.8	226.2	221.4	20.0
177,0	+/-2.5	234.6	237.0	232.2	19.0
190,5	+/-2.4	252.8	255.2	250.4	20.0

Courtesy of Highveld Steel and Vanadium Corporation Ltd.

Note: When a query on the chemical composition of products rolled from Highveld billets arises, the details as specified in JISG 0321 Table will govern.

To Specified Analysis Range: (Ladle analysis)

Carbon	8 points min. within range 0.10 – 0.50%
Manganese	40 points min. within range 0.4 – 1.60%
Silicon	30 points min. within range 0.15 – 0.60%
Sulphur/Phosphorus	0,05% max. each
Vanadium	sold to a specific minimum

Typical Residuals:	Nickel	0.10%
	Copper	0.06%
	Chromium	0.06%
	Molybdenum	0.02%
	Tin	0.02%
	Vanadium	0.02%

Length: 5 meters to 12 meters (some lengths available outside this range)

Shorts: Up to 4% of the tonnage ordered down to 3 meters.

Tolerances: Length: +/- 100mm

Straightness: Deviation from a tangential straight line within one meter of ends not to exceed 20mm.

Twist: A maximum of 1 degrees per meter or a maximum of 20 degrees over the whole length.

End Cut: Flame cut or hot sawn at Highveld's option.

1.1.1 Weldability:

All these mentioned structural steel grades may be welded using any of the standard metal arc and resistance welding processed, usually without any precaution. However, when welding heavy sections, BS 5135: 1984 "Metal-arc welding of carbon and carbon manganese steels" should be consulted to determine the preheat requirements at low heat inputs.

1.1.2 Corrosion protection:

Care should be exercised when specifying corrosion protection systems to ensure that the requirements of the specific application are met, without over-specification. Surfaces to be painted must be free of scale, rust and oil. Normally a zinc rich primer with one or two suitable top coats will be adequate, or refer to SABS 1200HC – 1988 for industrial/marine environment.

1.1.3 Tolerances:

Structural T-and H-sections are produced to conform to the dimensional tolerance limit laid down in 4: Part 1, 1980. The following tables show the different tolerances for different parts of the sections.

Table 2.3 – Tolerances on depth and off-centre of web for universal beams, columns and bearing piles.

Serial Size depth	Tolerances on Depth (D)	Tolerances on cross section	
		Off-centre of web (e) max.	Maximum depth at any cross section (C)
mm	mm	mm	Mm
Up to and including 305	+/-3	3.0	D + 5.0
Greater than 305	+/-3	5.0	D + 6.5

Courtesy of Highveld Steel and Vanadium Corporation Ltd.

Table 2.4 – Tolerances on flange width for universal beams, columns and bearing plates.

Serial size width	Tolerances on flange width (B)
mm	mm
Up to and including 130	+3 -2
Greater than 130 up to and including 210	+/-3
Greater than 210 up to and including 325	+/-4
Greater than 325	+6 -5

Courtesy of Highveld Steel and Vanadium Corporation Ltd.

1.1.4 Application:

I- and H-sections can be used for a wide range of structural elements, from light-weight purlins to columns, beams and bearing piles for industrial and multi-storey structures and bridges.

1.2 STEEL GRADES

Grading of steel is grouped in structural sections and flats, mechanical properties and chemical composition. They are graded by the various codes of practices in structural engineering. For the purpose of this review, we are limited to South African grading system.

Steel for structural sections is normally produced to SABS 1431 grades 300WA, 350WA and 450WA while grades with impact test requirement (WC and WDD) are available on enquiry. The South African Steel Construction Handbook published by the South Africa Institute of Steel Construction should be consulted for section properties.

Tables 2.5 and 2.6 in the following pages show a comparison of the mechanical and chemical properties respectively of the conventional steel grade and high-strength low-alloy steel.

Table 2.5 – Steel Grades based on mechanical properties

Grade	Yield Strength (min) MPa for thickness t, mm				Tensile strength, MPa	Elongation, (min) on guage length of		Charpy V-notch Impact test (100 mm x 10 mm test piece)	
	$t \leq 16$	$16 \prec t \leq 25$	$25 \prec t \leq 40$	$40 \prec t \leq 63$		200 mm	$5.65\sqrt{S_0^1}$	Min, J	Test temp ^0C
SABS 1431: 300WA	300	300	300	290	450/620	20	22	-	-
300WC	300	300	300	290	450/620	20	22	27	0
300WDD	300	300	300	290	450/620	20	22	27	-30
SABS 1431: 300WA	350	345	345	340	480/650	18	20	-	-
300WC	350	345	345	340	480/650	18	20	27	0
300WDD	350	345	345	340	480/650	18	20	27	-30
SABS 1431: 300WA	450	430	415		550/700	17	19	-	-
300WC	450	430	-		550/700	17	19	27	0
300WDD	450	430	-		550/700	17	19	27	-30
COR-TEN A	345	-	-	-	485	18	-	-	-
COR-TEN B	345	345	345	345	485	18	-	-	-

Courtesy of Macsteel, South Africa

Table 2.6 – Steel Grades based on Chemical Composition

Grade	C(max)	Mn	P	S(max)	Cu	Cr	Si	V	Nb(max)	Al	Ni(max)	Mo
SABS 1431 Grade 300WA	0.22	1.60(max)	0.05max	0.05	0.35max	0.3max	0.50max	0.10max	0.10	0.10max	-	-
SABS 1431 Grade 300WA	0.22	1.60(max)	0.05max	0.05	0.35max	0.3max	0.50max	0.10max	0.10	0.10max	0.30	0.10
SABS 1431 Grade 300WA	0.22	1.60(max)	0.04max	0.04	0.35max	0.3max	0.50max	0.20max	0.10	0.10max	0.30	0.10
Cor-Ten A	0.12	0.20/0.50	0.07/0.15	0.05	2.50/0.55	0.30/0.75	0.25/0.75	-	-	-	0.65	-
Cor-ten B	0.19	0.80/1.25	0.04max	0.05	0.25/0.40	0.40/0.65	0.30/0.10	0.02/0.10	-	0.015/0.06	0.40	-

Courtesy of Macsteel, South Africa

1.2.2 Atmospheric Corrosion Resistant Grades (COR-TEN steel)

The COR-TEN range of steel grades comprises of high-strength, low alloy, structural steel in which the alloy content has been formulated to give a protective oxide layer on the steel under atmospheric condition. It is produced in two grades:

1. COR-TEN A — flange thickness up to 12.7mm
   EN 10155-5355JOWP — conforms to ASTM A242 type 1

2. COR-TEN B — flange thickness over 12.7mm
   EN 10155-5355JOW — conforms to ASTM A242 type 2

They are available both as hot-rolled sheet and plate as well as cold-rolled sheet.

They are also graded in groups of mechanical and chemical composition.

1.2.3 Mechanical Properties of COR-TEN steel:

Table 2.7 – Mechanical Properties COR-TEN steel

Grade	Material thickness t. (mm)	Yield strength min (MPa)	Tensile strength min (MPa)	Elongation % min	
				In 50 mm	In 200 mm
COR-TEN A	$t \leq 12.7$	345	480	22	18
COR-TEN B	$12.7 \prec t \leq 100$	345	480	21	18
	$100 \prec t \leq 125$	315	460	21	-
	$125 \prec t \leq 200$	290	430	21	-

Courtesy of Iscor, South Africa

1.2.4 Chemical Composition of COR-TEN steel:

Table 2.8 – Chemical composition of COR-TEN steel

Grade	C	Mn	P	S	Si	Cu	Cr	Ni	V	Al
COR-TEN A	0.12 max	0.20/ 0.50	0.07/ 0.15	0.05 max	0.25/ 0.75	0.25/ 0.55	0.30/ 1.25	0.65 max	-	
COR-TEN B	0.19 max	0.80/ 1.25	0.04 max	0.05 max	0.30/ 0.65	0.25/ 0.40	0.40/ 0.65	0.40 max	0.02/ 0.10	0.015/ 0.060

Courtesy of Iscor, South Africa

1.2.5 Weldability of COR-TEN:

COR-TEN steel can be welded be means of any usual welding process such as manual metal arc, gas arc, flux-cored and sub-merged arc.

1.3 ISSUES RELATING CONVERSION TO A HIGH STRENGTH STEEL GRADE

It is a known fact that advanced high strength steels (HSS) can be up to four times stronger than ordinary mild steel. This finding was based on the premise that doubling the strength of steel allows the material thickness to be reduced by one third and makes the steel 30% thinner and in some cases 30% lighter.

HSS can also be called High Strength Low Alloy (HSLA) steel because they contain a smaller percentage of carbon (less than one-tenth of a percent) and only small amounts of very specific alloying elements. These elements are intended to utterly alter the microstructure of plain carbon steels, which is usually a ferrite-pearlite aggregate, and provide a very fine dispersion of alloy carbides in an almost pure ferrite. This eliminates the toughness-reducing effect of a pearlite volume fraction, yet maintains and even increases the materials strength by precipitation strengthening and by refining the grain size, which in the case of ferrite increases yield strength to up to 50% for every halving of the mean grain diameter. The conventional steels have yield strength that ranges from 210 MPa to 560 MPa.

This family of steels usually has a microstructure of fine-grained ferrite that has been strengthened with carbon and/or nitrogen precipitates of titanium, vanadium, or niobium (columbium). Adding manganese, phosphorus, or silicon further increases the strength. These steels can be formed successfully when users know the limitations of the higher-strength, lower-formability trade-off.

The steels which have yield strength over 560 MPa are sometimes called ultra-high-strength steels or super-alloys. They are categorized into 6 groups namely:

- Medium-carbon low-alloy hardenable steels
- Medium-alloy hardenable or tool and die steels
- High-alloy hardenable steels
- High-nickel maraging steels
- Martensitic stainless steels
- Semi austenitic precipitation-hardenable stainless steels

a. Medium-carbon low-alloy hardenable steels

These steels obtain their high strength by heat treatment to a full Martensitic microstructure, which is tempered to improve ductility and toughness. Tempering temperatures greatly affect the strength levels of these steels. The carbon is in the medium range and as low as possible but sufficient to give the strength. Impurities are kept to an absolute minimum because of high-quality melting and reforming methods. Their yield strength varies from 560 MPa to 800 MPa.

b. Medium-alloy hardenable or tool and die steels

These steels are used largely in aircraft industry for ultra-high-strength structural applications. They have carbon in the low to medium range and possess good fracture toughness at high-strength levels. In addition, they are air hardened, which reduces the distortion that is encountered with more drastic quenching methods. Their yield strength varies from 80 MPa to 1140 MPa.

c. High-alloy hardenable steels

The steels in this group develop high strength by standard hardening and tempering heat treatments. The steels possess extremely high strength in the range of 1240 MPa yield and have a high degree of toughness. This is obtained with minimum carbon content usually in the range of 0.20%; however, these steels contain relatively high amounts of nickel and cobalt, and are sometimes called the *9 Ni-4 Co* steels. These steels also contain small amounts of other alloying elements.

d. High-nickel maraging steels

This type of steel has relatively high nickel, and low carbon content. It obtains its high strength from a special heat treatment called maraging. These steels possess an extraordinary combination of ultra-high-strength and fracture toughness and at the same time are formable, weldable, and easy to heat treat. There three basic types: the steels with 18% nickel, 20% nickel and 25% nickel. These steels are available in sheet, forging billets, bars, strips and plate. Some are also available in tubing. Their yield strength varies from 1240 MPa to 1540 MPa.

e. Martensitic stainless steels

These steels are of straight chromium types. They contain 12-14% chromium and up to 0.35% carbon. This composition combines stainlessness with high strength. Numerous variation of this basic composition are available, all of which are in the Martensitic classification. Their yield strength varies from 1540 MPa to 1750 MPa.

f. Semi austenitic precipitation-hardenable stainless steels

The steels in this group are chrome-nickel steels that are ductile in the annealed condition but can be hardened to high strength by proper heat treatment. In the annealed condition the steels are austenitic and can be readily cold worked. By special heat treatment the austenitic is transformed to martensite and later a precipitant is formed in the martensite. The outstanding extra high strength is obtained by a combination of these two hardening processes. The term semi austenitic type was given these steels to distinguish them from normal stainless steels. They are also called precipitation hardening steels or PH steels. Their yield strength varies over 1750 MPa.

Some common characteristics when compared with conventional HSLA

When compared to lower-strength materials, high-strength metals usually have the following traits:

- Less stretchability – when tension is applied to the sheet metal to increase its surface area, the performance of these HSS as compared to conventional HSLA is poor,
- More brittleness and less ductility after forming – this creates a serious problem for parts needing reforming. Anytime high-strength material is permanently deformed, it is loaded with a great deal of stress. Excessively stressed, brittle parts may fail when subjected to shock.
- Poor stretch distribution – much like aluminum, high-strength materials strain locally.
- Higher springback values – something as simple as 90-degree bend can become a stamping problem. In other words, it is much difficult to fabricate high-strength steels into various sections.
- Larger press capacity – because of their increased yield, tensile and shear strengths, high-strength materials require more force to cut and form.
- More abrasiveness – high-strength materials requires dies that are made of premium tool steel that can withstand severe friction.

1.3.1 Economic issues relating to HSS

The principal economic advantages of high strength steels are derived from their high-strength and exceptional resistance to atmospheric corrosion. The high strength, when utilized, can provide a dividend in weight and freight savings and sometimes cost savings when compared to structural carbon steel. The enhanced atmospheric corrosion resistance permits the use of this steel in the unpainted condition in many applications.

1.3.2 Performance and limitations of HSS

a. Oxide formation

- The rapidity with which the steel develops its protective oxide coating and characteristic colour depends mainly on the nature of the environment. Generally, the weathering process will be more rapid and the colour darker in an industrial atmosphere, while the oxide formation will usually

be slower and the colour lighter in rural atmospheres. The tightly adherent atmosphere usually forms over a period of eighteen months to three years.

- Metal surfaces exposed to the south and west (in the northern hemisphere), develop a smoother and more uniform oxide than those exposed to the east and the north because south and west facing will be warmed to a greater extent by the sun. Exposure to higher temperatures permits more rapid conversion and dehydration of the corrosion products; whereas, surfaces exposed away from the sun react more slowly and the oxide exhibits a somewhat granular texture.
- The frequency of condensation and the time of wetness are factors that affect the period required for the formation of the oxide.
- The underside of exposed beams and sheltered exterior surfaces will generally develop a rougher texture than those surfaces boldly exposed to the sun, wind and rain.

b. Design consideration

- Surfaces of HSS that are wet for prolonged periods of time will corrode at an unacceptable rapid rate. Therefore, the detailing of members and assemblies should avoid pockets, crevices, faying surfaces or locations that can collect and retain liquid water, damp debris and moisture. Damp debris on HSS will cause accelerated corrosion. In addition to these precautions, all interior surfaces, including faying surfaces, not boldly exposed to the weather must be protected by paint.
- Surfaces of HSS members and assemblies that are not boldly exposed to the atmosphere are subject to moisture accumulation from numerous sources including capillarity and condensation. The designer must, therefore, exercise extreme care in the detailing of such elements, to assure

absolutely no possibility of moisture entrapment. All such unexposed surfaces, including faying surfaces, are to be treated as if they are carbon steel and must be protected by paint.

- Hollow steel members should be sealed to prevent entry of moisture. If this is not possible, provisions must be made to insure adequate drainage and ventilation so that the potential for entrapped moisture and accelerated corrosion is eliminated. Furthermore, if the member or structure is inaccessible for inspection and maintenance, protection of the interior surfaces should be considered.
- HSS which are to be covered by caulking or gaskets must be painted before being covered. This is to insure a positive seal and to provide adequate protection against corrosive of the steel that is covered. If this is not done the HSS will corrode at an unacceptable rapid rate.
- To minimize “oil canning” in large, flat assemblies, the minimum recommended thickness for bare HSS applications is 0.0478 inches – 1.2 mm.

c. Environmental precautions

- HSS is not to be used in the bare condition in atmospheres where high concentrations of corrosive chemical or industrial fumes are present, unless an in-depth study or a thorough evaluation of conditions so indicate suitability.
- Bare HSS is not to be buried as it will not provide corrosion resistance greater than carbon steel used in the same application. The protection must extend well above the ground line to ensure that the bare HSS does not come in contact with soil or debris at a later date.
- Bare HSS is not be submerged in water as it will not provide corrosion resistance greater than carbon steel used in the same application. Conventional methods of protection such

as concrete encasement, cathodic protection or a high quality coating such as coal tar epoxy generally are accepted. This protection must extend will above the high water line.

- Bare HSS must not be used in an application where the steel would be exposed to recurrent wetting by salt water, salt water spray or salt fogs because the salt residue will remain on the steel and will cause accelerated corrosion every time it is rewetted.
- Bare HSS is not to be used in an application where dense vegetation around the steel results in the prolonged retention of moisture on the steel surface.
- Bare HSS is not intended for interior applications.

d. Maintenance

- Bare HSS is not a maintenance-free material. Structures utilizing bare HSS should be periodically inspected to determine that all the joints and surfaces are performing satisfactorily. The frequency of inspection is to be established by the designer due to many variables which influence the protective oxide.
- Windows in HSS structures will require frequent cleaning during the period when the oxide coating is forming on the steel.
- Glass is not affected by the drainage products of HSS but staining and discoloration will become apparent once the surface has dried. Through the process of evaporation, minute particles of iron oxide which were held in suspension are deposited upon the surface of the glass. The film, which consists of airborne dirt in addition to the iron oxide, is generally difficult to remove by rinsing and may require the use of mild abrasive cleaner. Acid solutions should never be

used because the drainage products can attack not only the dark protective oxide, but the steel itself.

1.3.3 Fabrication and Handling of HSS

a. Forming

HSS can be cold-formed using conventional equipment and good shop practices. Slightly greater forming pressures and more liberal bending radii are required than are normally used for carbon steel. Bending with the axis transverse to the major rolling direction is preferred. Hot forming may lower mechanical properties, in which case they would be similar to those for annealed or normalized material.

b. Oxygen or Plasma-arc cutting

HSS may be oxygen or plasma-arc cut using good shop or field practices. Generally, some HSS does not require preheating, but most HSS, especially those with high MPa requires preheating before cutting.

c. Welding

HSS can be welded using good shop practice, by shielded metal-arc, submerged-arc, gas metal-arc, flux-coated arc, electroslag, electrogas, and electrical resistance processes.

d. Handling

Fabrication and erecting subcontractors must exercise care in the handling and storage of bare HSS sections and sub-assemblies. Sections stored outdoors in yards or at job sites must be positioned to allow for free drainage to avoid moisture pockets which may cause unsightly, uneven weathering.

e. Final cleaning

Any foreign materials which adhere to the steel after it has been erected and which would inhabit formation of the oxide should be removed as soon as practical.